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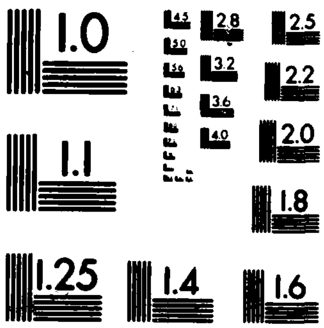

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OPERATIONAL USE OF AIR POLLUTION MODELS AT THE SPACE AND MISSILE RANGES

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15 November 1986

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The Space Shuttle exhaust ground cloud results from the exhaust plume from the Space Shuttle Main Engines and the Soild Rocket Boosters initially impinging on the launch complex and flame trench. The initial ground cloud is formed from high-temperature combustion products and vaporized flame trench water. The exhaust cloud rises to an altitude at which buoyant equilibrium with the ambient atmosphere is established. This occurs at an altitude of 1 to 2 km in a period of 5 to 10 min after launch. At this point, the kinematic transport phase commences. At stabilization, the exhaust cloud typically contains approximately 99 percent ambient air entrained during the cloud rise portion of its transport. The major rocket exhaust constituents are hydrogen chloride (HCL), carbon dioxide (CO_2), water vapor (H_20), and aluminum oxide (Al_20_3).

The REEDM (Rocket Exhaust Effluent Diffusion Model) computer code is currently used to provide a real-time dispersion prediction during each launch of the Space Shuttle at the

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Eastern Test Range (ETR). It has also been used to assess the environmental impact of future Shuttle launches at the Western Test Range. The REEDM includes basic mathematical expressions for atmospheric dispersion models, cloud-rise models for calculating the gravitational deposition of acid drops. Inputs are vehicle and other source parameters, meteorological parameters defining the state of the planetary boundary layer including turbulence parameters, and physical properties of the rocket exhaust cloud. This paper describes the model and discusses in detail recent improvements. It explains needs for the model and its role in both operational and planning modes of Shuttle support. It discusses the meteorological input parameter requirements, forecasting difficulties, and model results.

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1. INTRODUCTION

In their role of meteorological support to the Eastern Test Range (ETR), personnel of Air Weather Service's Detachment 11, 2nd Weather Squadron work closely with three models in the area of atmospheric pollution. One model deals with sound pollution, one with toxic spills, and the third with rocket exhausts. Versions of all three models are used at both the Western Test Range (WTR) and the ETR. The first two models are discussed elsewhere (Boyd and Overbeck 1986, Bobowicz 1985, Haugen and Taylor 1963, Kunkel 1983, and Taylor and Sch[illegible] 1986. This paper is concerned only with the Rocket Exhaust Effluent Diffusion Model (REEDM); primary as used at the ETR for Shuttle launches.

2. PROBLEM

2.1 Initial Cloud Constituents

At Shuttle launch an exhaust cloud is formed by atomization of deluge water followed by sweepout/coagulation of condensationally (water vapor) enlarged particulate aluminum oxide and absorption of gaseous hydrogen chloride. The normality of the resulting acid varies somewhat with sampling location and from launch to launch but typically has a value of two at the launch pad perimeter 400 meters from the launch platform in a direct line with the Solid Rocket Booster (SRB) exhaust duct (flame trench). The initial constituents of the exhaust cloud include large quantities of gaseous hydrogen chloride (HCl), particulate aluminum oxide (Al_2O_3) which spans the size range from submicron to greater than 50 micrometers in diameter, water vapor and heat. Afterburning of the hydrogen rich exhaust produces additional water vapor and carbon dioxide (CO_2) which accounts for the sum of the constituent masses exceeding the total exhaust mass. Table 1 summarizes the initial constituents of the Shuttle cloud (Keller and Anderson, 1985).

TWO SRB'S (AVERAGE L+15 SECS)

HYDROGEN CHLORIDE (21%)	2,260 Kg/s
ALUMINUM OXIDE (30%)	3,260 Kg/s
WATER (WITH BURNING) (29%) (820 GALS/SEC)	3,000 Kg/s
CO_2 (WITH AFTER BURNING) (41%)	4,450 Kg/s
NITROGEN (9%)	940 Kg/s
HEAT (WITH AFTER BURNING)	2.6×10^{10} cal/s

THREE MAIN ENGINES
(100 PERCENT POWER)

WATER(WITH AFTER BURNING) (480 GALS/SEC)	1,800 Kg/s
HEAT (WITH AFTER BURNING)	2.5×10^9 cal/s

Table 1. Initial constituents of the Shuttle exhaust cloud.

2.2 Environmental Impacts

Deposition of HCl and Al_2O_3 occurs at each launch. HCl is heavy in the near-field impact zone (22 hectares) ranging from 136.4 to 150 kilograms per hectare. Aluminum is heavy in the near-field impact zone ranging from 3.2 to 14.5 kilograms per hectare. Environmental loading for three recent Shuttle missions is summarized in Table 2 (Knott et al, 1985).

LAUNCH	TOTAL	Al	Al_2O_3	HCl
STS 11	7,100 Kg	140 Kg	280 Kg	3,000 Kg
STS 13	1,700 Kg	35 Kg	70 Kg	460 Kg
STS 14	7,900 Kg	160 Kg	320 Kg	3,300 Kg

Table 2. Near field environmental loading.

2.3 Deposition Variability

Actual deposition of the cloud exhaust varies considerably with atmospheric conditions. Of primary importance to deposition are the low level winds. Surface wind variability for the flights through 1984 are summarized in Table 3 (Jasper et al, 1985). Actual observed deposition for the first five Shuttle flights showed HCl reached the ground outside a five kilometer radius on three of the five missions. Areas where ground level deposition occurred are indicated in Figure 1 (Anderson, 1986).

SEQ NO	VEHICLE NO	TIME (EST)	LAUNCH DATE	WIND DIR	WIND m/s
1	STS-1	0700	4/12/81	125	3.8
2	STS-2	1010	11/12/81	345	8.9
3	STS-3	1100	3/22/82	050	2.3
4	STS-4	1100*	6/27/82	133	1.9
5	STS-5	0719	11/11/82	090	7.2
6	STS-6	1330	4/4/83	063	4.2
7	STS-7	0733*	6/18/83	010	1.9
8	STS-8	0232*	8/30/83	269	2.7
9	STS-9	1100	11/28/83	183	7.3
10	41-B	0800	2/3/84	000	0.0
11	41-C	0858	4/6/84	320	7.0
12	41-D	0842*	8/30/84	106	1.0
13	41-G	0703*	10/5/84	073	5.4
14	51-A	0715	11/8/84	024	7.5

*Eastern Daylight Time

Table 3. Surface winds (observed at 19.5m) for Shuttle launches through 1984.

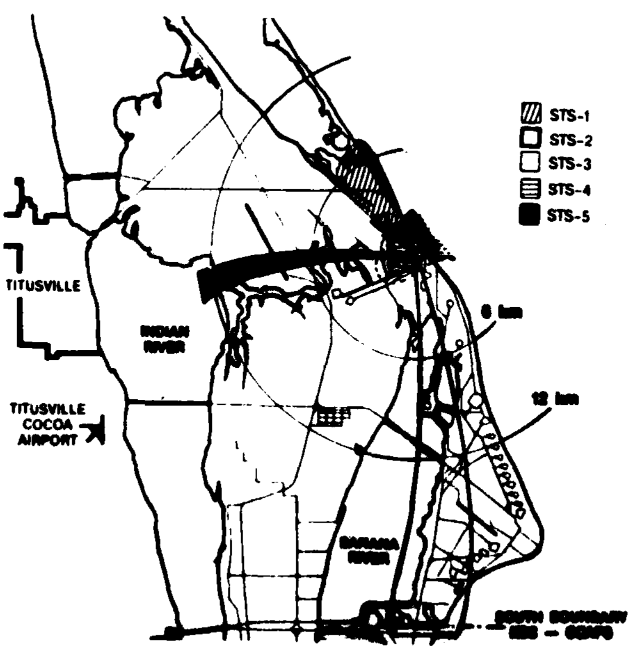

Fig 1. Ground deposition of HCl for STS 1-5.

3. OPERATIONAL MODEL

In order to forecast the area of deposition, the United States Air Force and NASA have cooperated to develop (with contract assistance from the H.E. Cramer Company Incorporated) the REEDM.

3.1 General Description

The REEDM computer code includes basic mathematical expressions for atmospheric dispersion models, cloud-rise models and models for calculating the gravitational deposition of acid drops. Inputs are vehicle and other source parameters, meteorological parameters defining the state of the lower 10,000 feet of the atmosphere (including turbulence parameters) and physical properties of the rocket exhaust cloud. During launches of the Space Shuttle, the exhaust ground cloud grows rapidly through entrainment and shortly after ignition, it lifts off the ground and rises to its stabilization height. Typically the top of the stabilized cloud produced by the Space Shuttle is more than 2 kilometers above ground level (AGL). By convention, this cloud is referred to as the ground cloud. The rocket engines of the ascending vehicle also leave an exhaust trail which extends through the troposphere and beyond. The REEDM computer program is designed to calculate peak concentration, dosage and surface deposition (resulting from both gravitational settling and precipitation scavenging) of ground cloud constituents. The current meteorological inputs to REEDM are the vertical profiles of wind direction, wind speed, air temperature, atmospheric pressure and dew point or relative humidity in the lower 3,048 meters (10,000 feet). It is possible to incorporate additional information about the current state of this layer which may be obtained from towers, remote sensing instruments or surface measurement stations. It's possible to replace any or all meteorological input data with forecast values (Boyd and Bowman, 1985).

The dispersion models used in REEDM are based on Gaussian model concepts which experience has shown to be best suited for most practical applications. A detailed discussion of Gaussian modeling concepts and alternative approaches is found in Pasquill (1975) and Gifford (1975). As pointed out in Dumbauld and Bjorklund (1973, 1975), the Gaussian approach, when properly used, ". . . is peerless as a practical diffusion modeling tool. It is mathematically simple and flexible, it is in accord with much though not all, of working diffusion theory, and it provides a reliable framework for the correlation of field diffusion trails as well as the results of both mathematical and physical modeling studies." In the REEDM, the exhaust material is assumed to be uniformly distributed in the vertical and to have a bivariate Gaussian distribution in the horizontal plane at the point of cloud stabilization. It follows from these assumptions that the models are of the general form identified with Gaussian models for vertical line sources of finite extent.

3.2 Program Components

The REEDM program currently used at the ETR is divided as illustrated in Figure 2. The five major parts are: meteorological inputs, source inputs dependent on launch vehicle and type of launch, cloud-rise and material distribution algorithms, the dispersion model algorithms (there are three--dosage/concentration, gravitational deposition and washout deposition) and output routines. The model for use at the WTR also contains a module which incorporates the influence of the complex terrain found there.

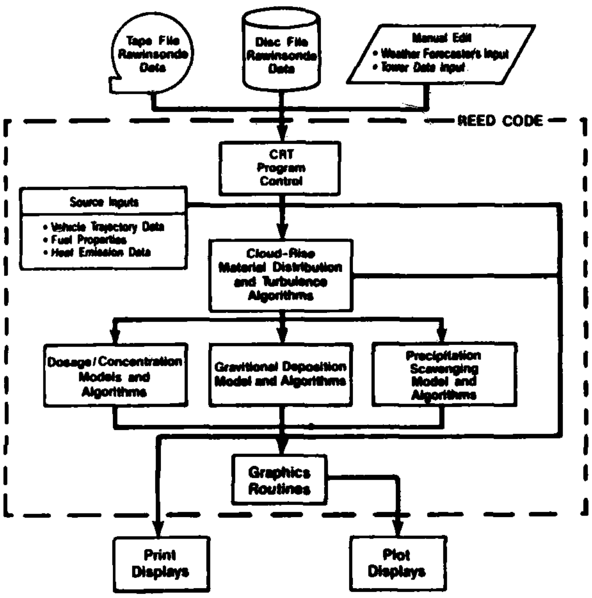

Fig 2. REEDM major components.

4. OPERATIONAL USE

The program meteorological inputs are initially input from disk files resident on the same computer system as the program. During launch support the meteorological data are updated by other support programs and/or replaced with forecast values. Although it is desirable to use all the sources of meteorological data, the REEDM program has been developed to execute with the rawinsonde data as minimum input. In support of each Shuttle launch, special rawinsonde releases are made at the times indicated in Table 4.

L-24	Hours
L-11	Hours
L-8.5	Hours
L-5	Hours
L-2.5	Hours
L-1	Hour
L-Ø	Hour

Table 4. Scheduled release times for rawinsondes used as REEDM input.

5. MODEL RESULTS

In general, the REEDM shows reasonable estimates of ground level deposition, provided the meteorological parameters input are representative. Certain weather conditions, such as breakup of morning inversions, onset of afternoon seabreezes, and frontal passages can create problems, if these conditions occur during the scheduled or delayed launch times. An illustration of general model agreement with observed results is seen in Figure 3 which represents the most recent successful Shuttle launch from the ETR. Selected levels of the input meteorological data are listed in Table 5.

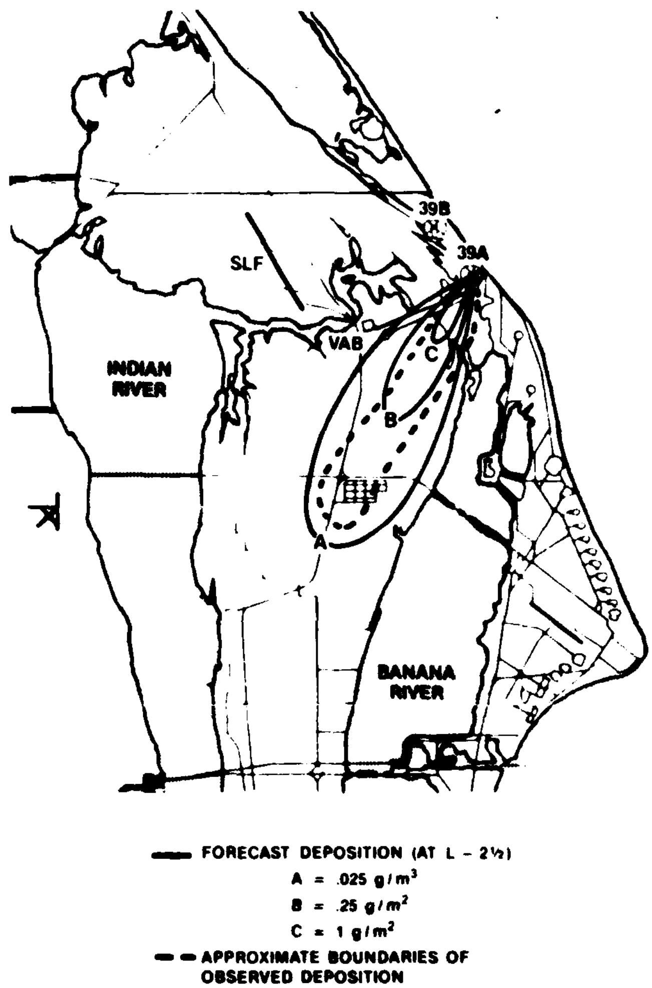

Fig 3. Forecast and actual ground deposition for Mission 61-C, 12 January 1986.

6. SUMMARY

Quality meteorological inputs are required with the current model to obtain valid output. Data are currently input by forecasters via editing of meteorological data files available at the ETR complex from rawinsondes released prior to launch and modified as required. Recent Shuttle launches indicate acceptable operational results, provided reasonably correct forecast data are input to the REEDM.

LVL No.	ALT ft	m	DIR deg	SPEED m/s	kts	TEMP (deg C)
1	16	4.9	20	4.1	8	16.4
4	161	49.1	25	9.3	18	18.5
8	571	174.0	28	8.7	17	15.8
10	1,992	607.2	41	7.7	15	12.0
11	3,000	914.4	50	6.7	13	9.5
16	4,000	1,219.2	352	2.6	5	9.3
18	5,000	1,524.0	278	4.6	9	8.4
20	6,000	1,828.8	264	4.6	9	6.7
22	7,000	2,133.6	268	3.6	7	4.2
25	8,000	2,438.4	351	4.6	9	4.4
29	10,000	3,048.0	26	4.1	8	1.4

Table 5. Selected levels of rawinsonde data for L-2.5 hours for Mission 61-C.

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